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BY
IRA H. WOOLSON.

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INVESTIGATION OF THE EFFECT OF HEAT UPON THE CRUSHING STRENGTH AND ELASTIC PROPERTIES OF CONCRETE.

BY IRA H. WOOLSON.

*Compliments of
the Author.*

It is well known that concrete in a building construction will withstand the attack of a fierce conflagration for some hours and retain its stability of form and strength. This has been proven by actual fires in buildings, and repeated severe fire tests upon full-sized floor units and partitions. It is also well known that concrete constructions have occasionally failed during conflagration and during official fire tests being made to determine the efficiency of some particular method of reinforcement. The causes of these failures were not always well defined. Usually they have been directly traceable to defective metal protection, unwise design of structural parts, or to the fact that the concrete was too green when subjected to the test. In some cases, however, the cause of failure was not entirely clear and much speculation has been rife as to just what degree of heat a concrete would stand before its strength and elasticity would be affected. This study was undertaken as an effort to throw some light upon this interesting subject.

The first step was to ascertain what previous work had already been done along the same line and the result obtained. A careful examination of the transactions of the engineering and scientific societies and the leading American technical journals for several years back furnishes very meager information.

The fire tests of reinforced concrete, such as have been conducted by the British Fire Prevention Committee in London, and by the writer in co-operation with the Bureau of Buildings in New York City and elsewhere, have for their purpose the determination of three properties: 1st, effect of a continuous fire at 1,700° or 2,000° F., for three or four hours; 2d, effect of the application of a strong stream of water at short range while the material is still at a high temperature; 3d, amount of deflection due to a load during the fire, and subsequent increased loading to 600 lbs. per

sq. ft. after the structure has cooled. The methods of construction and character of test are regulated by municipal specifications in this country, and by rules of the British Fire Prevention Committee in England.

The concretes used have included trap, limestone and cinder, and were usually 1-2-4 or 1-2-5 mixtures. The reports of numerous tests of this character were examined and in most instances the concrete stood the heat and subsequent loading well, but the results were general and referred to the quality or resistance of a particular construction rather than to specific data regarding the concrete itself. Large numbers of tests of compressive strength and elastic properties have been made upon concrete of various composition and after different preliminary treatments, but no records were found in which the concrete was heated prior to testing.

The report of the U. S. Arsenal at Watertown, Mass., for 1902, contains data of tests of neat cement cubes of several brands, which were heated before crushing. A synopsis and discussion of these is given by James E. Howard in the May, 1905, issue of "Cement," and some of his conclusions are given, since it is fair to assume that the action of neat cement under heat should be at least a slight criterion of that of concrete. The following is a summary of the results reported by Mr. Howard.

TABLE I.—EFFECT OF PREVIOUS HEATING ON CRUSHING STRENGTH OF NEAT CEMENT AND 1: 1 SAND MORTAR.

(Watertown Arsenal, 1902. J. E. Howard.)

COMPOSITION.		Not Heated	Ultimate Crushing Strength in lbs. per sq. in After Heating.							
Cement	Sand									
Temperature F.	200°	300°	400°	500°	600°	700°	800°	900°
1 Alpha*	9167	8830	7920	9190	9400	9333	8217	8060
1 Alpha†	12480	14447	13767	13910	12787	12130	12130	9985
1 Dyckerhof*	5017	...	...	...	...	4313	3483	4280
1 Mankato*	1867	1657	1876	1066	1603	1453	1496	1400
1 Mankato†	3873	4043	3523	3810	4133	4133	3957	3900
1 Mankato*	...	1	538	401	432	...	471	...	381	...
1 Mankato†	...	1	2170	2067	1953	...	2063	...	2240	...

* Cubes set in air.

† Cubes set in water.

It was desired to ascertain the effect of elevation of temperature alone without introducing internal strains incident to a state of unequal temperatures in different parts of the specimen. The test pieces were 4-in. cubes cast slightly more than a year previous. Tests were at intervals

of from 4 days to 4 months after heating. The cubes were gradually raised to the recorded temperatures. The heating took one hour, the maximum temperature was held one hour, and the specimens were then allowed to cool slowly in dry sawdust or powdered asbestos. During the heating the specimens developed fine cracks; these were hardly visible immediately after cooling nor were they one day later. Four days after heating they were generally developed and at eleven days they were nearly at a maximum. The effect upon the crushing strength was not serious when the cracks were fine, as the parts fitted together under pressure.

Table I shows the variation in ultimate crushing strength of the cubes. Each result is an average of three tests. This indicates that there is no decrease in strength up to a temperature of 600° Fahrenheit, but for higher temperatures the strength diminishes quite rapidly.

A search for previous similar investigations was so fruitless, it was evident that our explorations were to be conducted in practically an untrodden field, so the method of procedure was the next consideration, the desire being to make the conditions conform as nearly as possible to practice.

Since all the factors which enter the concrete problem are variables, it is extremely difficult to arrive at even a partial solution under any one set of conditions. There is, first, variation in the quality of the cement; second, difference in size, sharpness and cleanness of the sand; third, size and quality of the stone, gravel, slag or cinders used; fourth, variations in the proportions of the three solid ingredients and the amount of water used, and, fifth, method of mixing and treatment after molding, including age before testing. This latter is quite important, for it is well known that the strength of concrete increases rapidly for a period of six to twelve months after casting and continues to increase slightly up to two or more years.

It was decided to make the concrete a 1-2-4 mixture of cement, sand and $\frac{3}{4}$ -inch broken stone, this being a common mixture used in constructing reinforced concrete floors. The cement was supplied by your Committee on Concrete and consisted of a mixture of different brands of the best grades of Portland. The sand was taken from a quantity being used in the erection of a new building on the University grounds. It was of medium size (90 per cent. passing a 12-mesh sieve), fair quality, and not especially clean. Two varieties of stone were employed, Hudson River blue limestone and Hudson River trap-rock. Two sets of specimens were prepared which were duplicates in every respect, except that one contained limestone and the other trap-rock.

The mixing and casting were done by a laborer familiar with concrete work. A moderately wet mixture was used, tamping in the molds being continued until the surface of the concrete became flushed with water.

The investigation had three primary objects. First, to ascertain at what temperature the concrete began to lose crushing strength due to heat treatment; second, the rate at which strength decreased as a result of increase of heat, and last, but not least, the effect of varying temperatures upon the elastic properties of the concrete; the purpose being to determine if the elasticity began to diminish prior to the strength or concurrently with it. It was decided to make 500° F. the initial heat, and then to increase the temperature by intervals of 250° F. to 2,250° F., testing specimens at each temperature. The upper temperature limit was well above the average of a burning building, which is conservatively estimated by most experts as ranging from 1,500° to 2,000° F.

The determinations of crushing strengths were made upon 4-inch cubes; for the elastic properties, prisms 6x6x14 inches, were used, the height being sufficient to allow the measuring of compression on a length of 12 inches, and the cross-section being large enough to avoid the necessity of considering the specimen as a column.

To establish the quality of the concrete, three cubes and three prisms of each composition were first tested without being heated; then three cubes and two prisms of each composition were tested at each temperature.

Method of Heating.—The heating to 1,750° F. was done in an oven type of gas furnace. The furnace had a capacity of twelve cubes or two prisms and also allowed room for protecting them from the flames with fire bricks placed around the sides and top. The specimens were kept from contact with the floor by being supported on iron rods. Above 1,750° F. the heating was done in a large gas crucible furnace.

To insure equal heating throughout the specimen, the rate of heating was arbitrarily fixed at 45 minutes to reach the first 500°, and 30 minutes for each successive 250°, the maximum heat being held 10 minutes before removing the specimen. This method subjected the prisms to a shorter period of heating than the cubes for every temperature except 500°, because the former were brought to

the required temperature, held there, and then removed. The latter were charged into the furnace 12 at a time, brought to the proper heat, held there 10 minutes, and three cubes removed; then the temperature was raised 250°, and held again. This being continued until the last cubes were removed. Good results were

TABLE II.—COMPRESSIVE STRENGTH OF 4-INCH TRAP-ROCK CONCRETE CUBES.

Specimen No.	Age in Days.		Heated to Degrees F.	Ultimate Strength lbs. per sq. in.	Condition after Heating.
	Before Heating.	Between Heating and Testing.			
1....	32	....	Unheated	1903	
2....	32	....	"	1913	
3....	32	....	"	1892	
4....	36	2	500	1808	
5....	36	2	500	2100	
6....	36	2	500	1853	
7....	36	2	750	1880	
8....	36	2	750	1690	Slight cracks.
9....	36	2	750	1950	
10....	36	2	1000	1547	Brittle and full of minute cracks.
11....	36	2	1000	1273	Same.
12....	36	2	1000	1418	Same.
13....	36	2	1250	1110	Brittle and had several small cracks.
14....	36	2	1250	1163	Same.
15....	36	2	1250	1459	Same.
16....	50	10	1500	1265	Few cracks; appears sound.
17....	50	10	1500	1802	Sound; no cracks.
18....	50	10	1500	1602	Same.
19....	50	10	1750	644	Full of cracks.
20....	50	10	1750	1220	Same; one crack extending entirely around.
21....	50	10	1750	904	Full of cracks.
22....	44	9	2000	680	Full of cracks; one extending around 3 sides.
23....	44	9	2000	1072	Few cracks; surface was pitted.
24....	44	9	2000	790	Same.
25....	44	9	2250	458	Slightly fused on one edge; few cracks.
26....	44	9	2250	626	Very much fused on bottom.
27....	44	9	2250	420	Full of cracks; slightly fused on one edge.

obtained for the cubes for all temperatures, but it is doubtful if the prisms were uniformly heated at temperatures under 1,250°, as will be explained later.

Temperatures were measured continuously by a Le Chatelier pyrometer. The thermo-couple was located about 4 inches above the floor of the furnace and closely surrounded by the specimens.

After heating, the specimens were immediately removed from the furnace and allowed to cool in the air. The testing was done at intervals up to three weeks subsequent to the heating.

Method of Testing.—The tests were made upon a Riehle testing machine of 100,000 pounds capacity. The cubes were faced on the upper surface with plaster of paris, the lower face being in

TABLE III.—COMPRESSIVE STRENGTH OF 4-INCH LIMESTONE CONCRETE CUBES.

Specimen No.	Age in Days.		Heated to Degrees F.	Ultimate Strength lbs. per sq. in.	Condition after Heating
	Before Heating	Between Heating and Testing.			
1....	34	....	Unheated	1068	
2....	34	....	"	1843	
3....	34	....	"	1640	
4....	38	3	500	1227	Somewhat brittle.
5....	38	3	500	1200	Same.
6....	38	3	500	1184	Same.
7....	38	3	750	1122	Brittle, and gave metallic sound if struck.
8....	38	3	750	1440	Same.
9....	38	3	750	1170	Same.
10....	38	3	1000	923	Stone slightly calcined.
11....	38	3	1000	991	Same.
12....	38	3	1000	1214	Same.
13....	38	3	1250	988	Clacination throughout.
14....	38	3	1250	1038	Same, but appeared sound.
15....	38	3	1250	903	Same, surface discolored.
16....	44	3	1500	680	Same, edges chipped.
17....	44	3	1500	778	Same, full of small cracks.
18....	44	3	1500	838	Same, crumbles easily.
19....	44	3	1750	832	Same, and discolored.
20....	44	3	1750	684	Very fragile.
21....	44	3	1750	922	
22....	44	3	2000	...	Crumbled on cooling.
23....	44	3	2000	...	Same.
24....	44	3	2000	...	Same.
25....	44	3	2250	...	Same.
26....	44	3	2250	...	Same.
27....	44	3	2250	...	Same.

all cases smooth enough to require only a few sheets of blotting paper to insure a firm bearing. The pressure was applied to the top and bottom faces as determined by their position in the mold. The pressure was applied very slowly and steadily until the specimen failed.

The prisms were faced on both ends with plaster and compressions measured on a gaged length of 12 inches by an electric

contact extensometer adjusted to the specimen as shown in Fig. 1.* The load was applied at the same rate as for the cubes. It is important that the load should not be applied faster than the concrete will adjust itself to the new stresses, or a fictitious strength

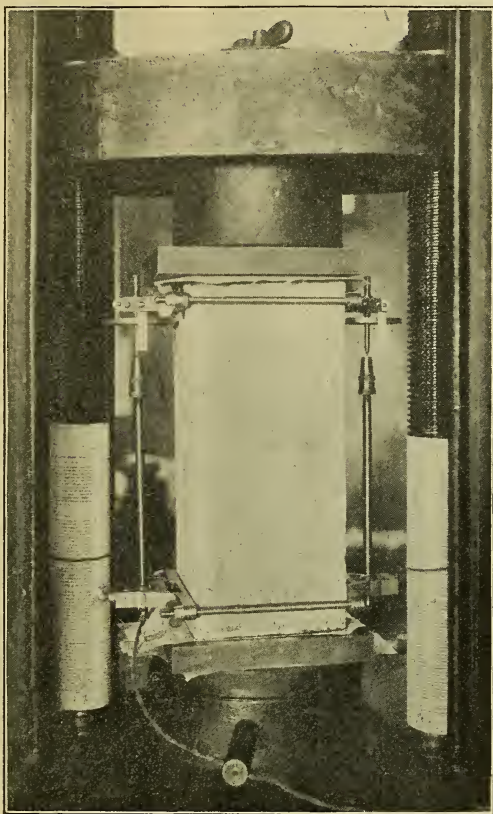


FIG. 1.

will be recorded and instrument readings will alter until an equilibrium has been established. Compressions were measured at loads of 0, 25, 50 and 100 pounds per square inch, and then by increments of 200 pounds per square inch, until indications of failure

* Acknowledgment is made to the Engineering News Publishing Company for the cuts used in this paper.

forced the removal of the instrument. Sets were measured one minute after the removal of each load, this interval being found sufficient to allow the specimen to assume a stable condition.

It was originally intended to have the concrete at least sixty days old before testing, but owing to an unavoidable delay in securing part of the material it became necessary to test the specimens

TABLE IV.—COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY OF TRAP-ROCK CONCRETE PRISMS.

Specimen No.	Age in Days.		Heated to	Ultimate Strength in lbs. per sq. in.	E at 200 lbs. per sq. in.	E at 600 lbs. per sq. in.	E at 1,000 lbs. per sq. in.	Condition after Heating.	Specimen No.
	Before Heating.	Between Heating and Testing.							
2 ..	33	....	...	1,560	3,450,000	2,140,000	1,700,000	Specimen in good condition	2
3	33	....	...	1,820	3,180,000	3,000,000	2,440,000	Same	3
4	34	....	...	1,725	3,340,000	2,070,000	1,610,000	Same	4
10A ..	48	6	500° F.	1,404	715,000	902,000	863,000	Same	10A
11A ..	48	6	500°	1,970	834,000	950,000	1,040,000	Same	11A
12B ..	49	3	750°	1,250	490,000	526,000	472,000	Very minute cracks apparent	12B
13B ..	49	3	750°	835	400,000	461,000	.....	Appeared sound, but brittle	13B
16C ..	50	5	1,000°	735	128,000	171,500	.....	Same, had a metallic ring when struck	16C
17C ..	50	5	1,000°	1,100	160,000	212,000	.....	Same	17C
20D ..	54	3	1,250°	910	89,000	122,000	.....	Surface covered with small cracks	20D
21D ..	54	3	1,250°	1,055	83,000	125,000	.....	Same	21D
24E ..	56	9	1,500°	250	19,400	.....	.....	Very bad specimen, sides warped and shattered ..	24E
25E ..	56	9	1,500°	...	.....	.....	.....	Worse than 24E	25E

when a little over a month old. This was much to the disadvantage of the concrete in the fire tests, and it also accounts for the rather low values obtained in the tests of unheated specimens.

Results.—Table II. gives the ultimate crushing strength of the 4-inch trap cubes which were heated to various temperatures and crushed after cooling. No appreciable effect upon the strength can be noted until a temperature of 750° is reached. This gave

slightly lower average strengths. Beyond 750° the decrease was marked, though there were two or three exceptions to the rule notable at $1,500^{\circ}$, where two of the specimens gave remarkably high results. Why these cubes should have withstood the heat so much better than the others is not known. With the above exception, the surface of all specimens heated over 750° was covered with minute cracks. At $2,250^{\circ}$ F. the cubes were slightly fused, due to the fact that fire-brick protection was displaced in removing previous specimens, and the remainder were more or less exposed to direct contact with the flames.

Table III. gives similar data for the limestone cubes. The three unheated cubes show an average strength only slightly inferior to that of the trap mixture. Heating to 500° , however, gave a great loss in strength. There were no evidences in the appearance of the cubes indicating this deterioration. No further weakness resulted

at a temperature of 750° , but beyond this the loss of strength continued. After heating to $2,000^{\circ}$ and $2,250^{\circ}$ the cubes appeared strong and in good condition while hot, but when cold they began



FIG 2.—Appearance of 4-in. Cubes of Limestone Concrete Three Days After Heating to Temperature of $2,000-2,250^{\circ}$ F.

to disintegrate, and at the end of three days their appearance was as shown in Fig. 2. No attempt was made to test these specimens.

Table IV. contains the results of the test upon the elastic properties of trap-rock prisms. Three curves were also plotted for each specimen: 1, total deformation; 2, set; and 3, true elastic. The latter was obtained by Professor Bach's method, viz., by subtracting from each total deformation reading the corresponding set reading. Modulus of elasticity (E) was figured for three points of the true elastic curve.

Taking the age into consideration the values for the unheated specimens compare favorably with the results of other investigators. As is usual, the value of E diminishes with increase of pressure. With the heated specimens this is not so marked; in fact, it is often the reverse, particularly with the intermediate loading. There is, however, a very marked decrease in the value of E due to the heating. This change becomes very apparent even with a temperature of 500° and the value gradually decreases with the increase of heat. There were some erratic results, but later investigation makes it quite certain they were due to imperfect heating.

After the elastic measurements on the prisms were completed the extensometer was removed and the specimen loaded to failure. The ultimate crushing strengths which were thus obtained are given.

Table V. gives the same data for limestone prisms. The moduli for the unheated specimens are about the same as those obtained by the writer on a series of similar tests recorded in *Engineering News* of June 1, 1905, the average value of E obtained there being approximately 3,600,000 for a sand-lime-stone concrete 55 to 58 days old, and the average here found being 3,300,000 for prisms 20 days younger of like composition.

The value of E falls rapidly with increase of heat applied, the same as for the trap-rock mixture.

The surfaces of the prisms of both mixtures were covered with minute cracks after being subjected to over 750° and then cooled. These cracks increased in number and size as the heat became higher, and at $1,500^{\circ}$ the prisms began to warp and disintegrate on cooling. This deterioration increased with time, and at the end of nine days one prism of each mixture was so badly crumbled it was unfit for test. The others were very much weakened. This disintegrating effect is probably due to the swelling of the cement as a result of recalcination.

The curves of all the heated specimens show a large deformation in the early part of the test when the loads were comparatively light. This gradually lessens as the loads increase and the middle portion of each curve approaches a straight line and then falls off again when ultimate failure begins. The large deformation at first is doubtless due to the closing up of the numerous fire cracks previously mentioned.

TABLE V.—COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY OF LIMESTONE CONCRETE PRISMS.

Specimen No.	Age in Days.		Heated to Degrees F.	Ultimate Strength in lbs. per sq. in.	E at 200 lbs per sq. in.	E at 600 lbs. per sq. in.	E at 1,000 lbs. per sq. in.	Condition after Heating.	Specimen No.
	Before Heating	Between Heating and Testing.							
5....	30	....	...	1,427	3,000,000	1,715,000	1,028,000	.....	5
6....	30	....	...	1,452	3,340,000	2,330,000	2,080,000	.....	6
7....	30	....	...	1,246	2,500,000	1,715,000	1,390,000	.....	7
8A..	44	4	500°	1,568	700,000	352,000	476,000	Specimen in good condition.	8A
9A..	44	4	500°	1,207	1,330,000	1,176,000	972,000	Same	9A
14B..	45	7	750°	1,110	500,000	333,000	344,000	Not smooth on sides	14B
15B..	45	7	750°	1,214	222,000	294,000	286,000	Good condition	15B
18C..	51	4	1,000°	932	157,000	200,000	.....	Stone on edge slightly calcined	18C
19C..	51	4	1,000°	1,145	172,000	285,000	.....	Same	19C
22D..	57	3	1,250°	840	92,500	13,650	.....	Stone entirely calcined to depth of 2-in.	22D
23D..	57	3	1,250°	740	59,000	10,000	.....	Same	23D
24E..	57	19	1,500°	...	.....	.....	.....	Stone entirely calcined, sides warped and shattered ...	24E
25E..	57	19	1,500°	810	83,300	133,000	.....	Same as 24E to lesser degree	25E

A peculiar characteristic of many set curves for both mixtures is the tendency they have to reverse direction and go back towards the axis. A conspicuous example appears in Fig. 4. No satisfactory explanation for this behavior has been suggested.

It will be noted that the elasticity of the specimens decreased rapidly with the increase of heat. This is clearly shown in Figs. 3 and 4, where all three curves for each test of *three typical speci-*

mens of each mixture are plotted to the same scale, showing the character of the total deformation, set and elastic curves without heating, and the corresponding curves for specimens which had been heated to $1,000^{\circ}$ and $1,500^{\circ}$ F. respectively.

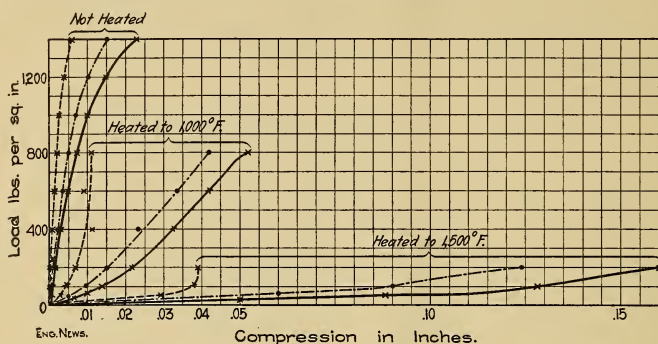


FIG. 3.—Typical Curves of Trap Concrete.

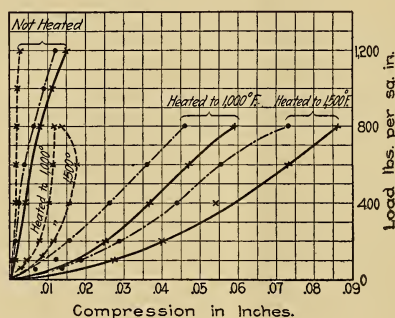


FIG. 4.—Typical Curves of Limestone Concrete.

FIGS. 3 AND 4.—Typical Stress-strain Curves of Normal Concrete and Concrete Previously Exposed to Temperatures of $1,000$ and $1,500^{\circ}$ F.

Test pieces 6×6 ins. 14 ins. high, of $1:2:4$ concrete. Compressions measured on 12 -in. length. Test pieces heated at ages of 33 to 57 days, then cooled slowly, and tested 3 to 19 days later.

Full lines give total deformation.

Dotted lines give sets.

Dot-and-dash lines give true elastic deformation = total deformation minus set.

The "true elastic" curves of *all* the prisms tested are grouped in Figs. 5 and 6, which indicate very plainly the gradual decrease of elasticity due to heating of the concrete.

The gradual decrease in strength of both cubes and prisms due to heat treatment is shown by the curves in Fig. 7. In general, the

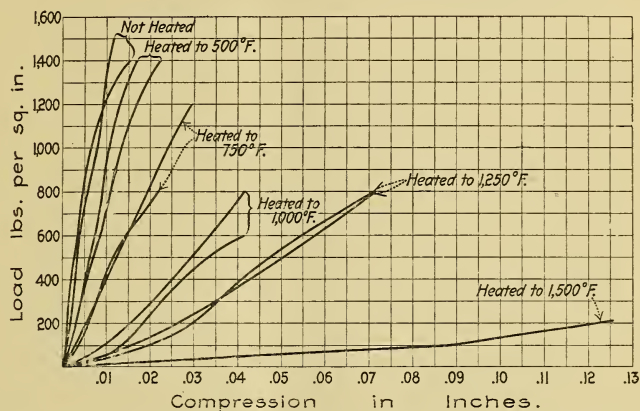


FIG. 5.—Elastic Curves of All Prisms of Trap Concrete.

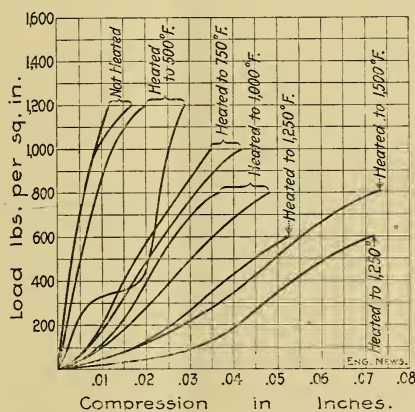


FIG. 6.—Elastic Curves of All Prisms of Limestone Concrete.

FIGS. 5 AND 6.—Elastic Curves of Normal Concrete and Concrete Previously Exposed to Various Temperatures from 500° to 1,500°F.

Test pieces 6 x 6 ins., 14 ins. high, of 1 : 2 : 4 concrete. Compressions measured on 12-in. length. Test pieces heated at ages of 33 to 57 days, then cooled slowly, and tested 3 to 19 days later.

Two specimens tested for each temperature.

All curves give true elastic deformation = total deformation minus set.

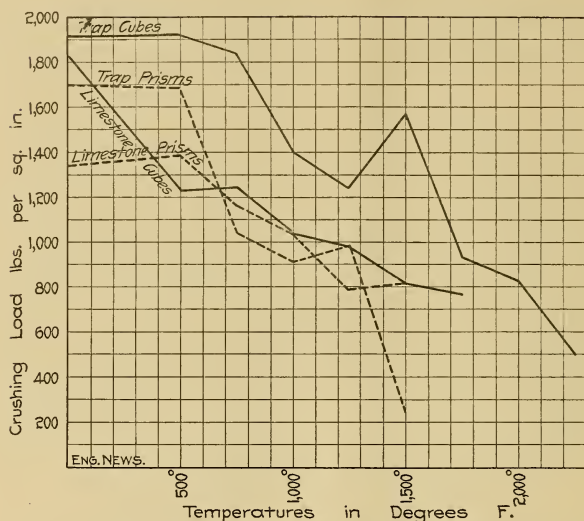


FIG. 7.—Curve of Crushing Strength.

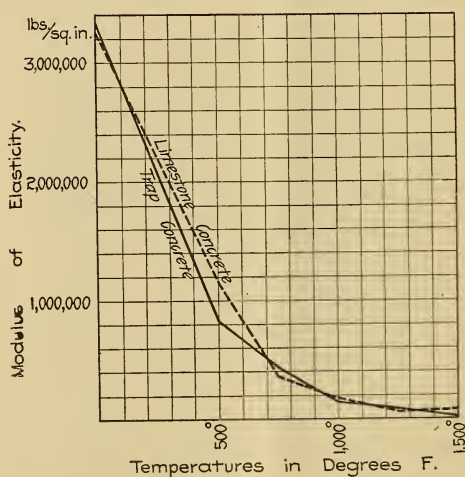


FIG. 8.—Curve of Modulus of Elasticity.

FIGS. 7 AND 8.—Variation of Crushing Strength and Elasticity of Concrete With Temperature of Previous Heat Exposure.

Test pieces 4-in. cubes, 6 x 6 ins. x 14-in. prisms; all of 1:2:4: concrete.

Curves of elasticity give the modulus at unit stress of 200 lbs. per sq. in.

trap-rock mixtures were the stronger. There were some irregularities, which undoubtedly resulted from defective heating. Fig. 8 shows graphically the drop in the value of E for both mixtures due to heating.

As stated in the early part of this paper, the length of time a specimen should remain in the furnace to bring it to a certain heat was fixed beforehand, and with the 4-inch cubes the rate of heating employed appeared to give them uniform treatment throughout.

It was supposed the prisms would heat uniformly also in the time allowed, but subsequent results raised doubts regarding this. However, owing to the delays previously mentioned it was now too late in the season to duplicate the specimens and get them tested this spring, so the tests were completed and this report is rendered upon the data obtained.

Table VI. gives the actual times of heating for each class of specimen. It is known now that the time allowed for the prisms was not nearly sufficient to insure uniform temperature throughout. This is particularly true for the low temperatures. With the high temperatures the variation was probably not so great.

A test was recently made of the conductivity of the concrete in the prisms under the conditions of heating employed in the tests,

TABLE VI.—PERIOD OF HEATING THE TEST SPECIMENS.

Specimen.	Heated to Degrees F.	Time.
4-in. cubes	500°	55 minutes.
"	750°	1 hr., 35 min.
"	1,000°	2 " 15 "
"	1,250°	2 " 55 "
"	1,500°	2 " 55 "
"	1,750°	3 " 35 "
"	2,000°	3 " 55 "
"	2,250°	4 " 35 "
Prisms	500°	55 minutes.
"	750°	1 hr., 25 min.
"	1,000°	1 " 55 "
"	1,250°	2 " 25 "
"	1,500°	2 " 55 "

and it was found that by allowing 1 hour 15 minutes to bring the furnace temperature up to 750° F., and then holding that temperature constant, it required 2 hours 40 minutes more for the interior of two different prisms to attain the same temperature. Then raising the furnace temperature to 1,000° in 30 minutes, it required 1 hour 10 minutes more for the prisms to become uniformly heated throughout. The tests were made by imbedding thermo-couples

in the middle of the prisms, and connecting them by switch to the same galvanometer on which the couple in the furnace was recording. The concrete on which this test was made was 28 days old. In this instance it required 5 hours 35 minutes to obtain a temperature of $1,000^{\circ}$ F. through 3 inches of concrete where the specimen was surrounded by heat on all sides, with no radiation possible.

This last experiment proved that the concrete had a very low conductivity and made certain the fact that the prisms tested had not been heated throughout to the temperature with which they are credited. At the same time, the writer believes, it explains the apparent discrepancy which exists between the results of these tests and some very satisfactory fire tests which have been made upon full-sized floor constructions. In a test of the latter character the fire is applied to one side only, and, although a heat of $1,700^{\circ}$ to $2,000^{\circ}$ is maintained for four hours, the concrete is such a poor conductor of heat that only a small portion of it ever reaches a temperature which would cause it to deteriorate to any great extent.

The writer is fully aware that the data presented are very incomplete and by no means sufficient upon which to base conclusions. The problem is an extremely difficult one, and at the same time very important. He plans to continue the investigation as opportunity offers and hopes that other investigators will give it their attention, so that in the near future some really reliable data may be obtained.

The investigation of this subject, together with the experiments detailed in this paper, was undertaken at the request of the Joint Committees on Concrete and Reinforced Concrete of this Society, and forms part of the broad inquiry into the properties of that material which is being conducted in the various testing laboratories and technical schools of the country, under the general supervision of that Committee.

The actual work of the investigation, together with the calculations and plotting of the curves, was done under direction of the writer by Messrs. F. H. Burch, Jr., and W. H. Connell, Jr., two students in the Department of Mechanical Engineering at Columbia University, and formed the subject of a research thesis problem in their senior year. Much credit is due these men for their faithful devotion to the work, and their energy in performing the tedious details. The presentation of this paper at this time was made possible only by their conscientious assistance.

DISCUSSION.

MR. R. W. LESLEY.—This paper seems to involve two important questions: one, the chemical character of cement, and the other going to the strength of beams and floor construction exposed to fire. The general proposition is one which should bring a good many engineers to their feet. Mr. Lesley.

MR. WILLIAM KENT—There is one practical question I should like to ask. Suppose a warehouse is built of concrete, with a factor of safety of four, and there should be a fire in the combustible material stored in the warehouse—suppose, now there is reason to suspect that while the building did not fail, and the fire was put out, still it lasted such a long time that the concrete might have been heated to 1,500° F., and that the factor of safety of the building is possibly reduced to below two. Should the building be condemned and rebuilt, so far as the floor and the parts sustaining the pressure of the load are concerned? Mr. Kent.

MR. LESLEY.—The Chair will answer that from a practical experience. In Belgium there was a fire in a large knitting mill constructed under the Hennebique System entirely of concrete. Under the contract it was provided that certain tests of the floors and building should be had before acceptance. All the requirements were met and the owners took possession. Subsequently, there was a fire in the mill, the machinery was badly injured, some of the shafting twisted and a great deal of combustible matter was destroyed. The mill itself, however, was not injured in any way. Before starting up again, the owners, who held a guarantee from the Hennebique Company, wanted to assure themselves that the mill walls, floors, etc., still met the requirements of the original specifications, and that the Building Laws of Belgium had been complied with. Of course, the mill was a little bit older than when it was first constructed, and at the inspection after the fire it was ascertained that there was a gain of 20 per cent. in strength in every one of the required tests. Possibly that answers the question. Mr. Lesley.

MR. RICHARD L. HUMPHREY.—I think the tests that Prof. Mr. Humphrey.

Mr. Humphrey. Woolson has just described to us are extremely interesting and valuable and open up important fields in the investigation of properties of cement. It has given rise to a number of thoughts which I should like to offer by the way of comment. I understood the tests were made on cubes about sixty days old.

Mr. Woolson. MR. IRA H. WOOLSON.—Thirty to forty days.

Mr. Humphrey. MR. HUMPHREY.—In studying the effect of heat on hardened mortar or concrete, it is necessary to understand the process of hardening. From the moment the clinker is reduced to an impalpable powder, until it is finally hydrated, it is constantly undergoing changes produced by the reactions which tend to convert it from an unstable to a stable compound. It is doubtful whether these changes ever cease. The process of hardening in a cement is one of hydration resulting from the water which is added to it or which is absorbed from the air. The process of hardening in a mortar or a concrete is due to the crystallization or hydration of the cement which, during the mixing has been forced into the pores in the surfaces of the sand, gravel, stone, etc., in a plastic condition. This is the bond which holds the sand, stone or gravel together, and is destroyed at a temperature sufficiently high to drive off the water of crystallization.

The effect of heat, therefore, is one of degree, depending on the age of the concrete or mortar and on the intensity and duration of the heat. If the heat conditions are right the mass will be eventually reduced to its original state, prior to hardening. The larger the mass the more slowly is this water driven off, as it requires time for the water from the interior to reach the surface.

In addition to this water of hydration, there is also present in the void spaces of the mortar or concrete a certain amount of entrained or hygroscopic water, which, under the action of heat, expands, with a force sufficient to disrupt the mass—especially if very green. The amount of water will depend on the porosity, and decreases, therefore, as the density increases.

Green concrete when subjected to the action of heat, undergoes a sweating process in which this entrained water is gradually brought to the surface, this phenomenon disappearing with the absorption of the water either by the air or by the concrete in hardening. The expansion of this water under heat, which draws it to the surface, frequently disrupts the mass.

Professor Woolson's tests were made on six-inch cubes of green concrete. The superficial area of a six-inch cube bears a large ratio to the mass. The action of fire on such a test piece would be much greater than would be the case with a larger mass, such as the floors and walls of a building where the action would be largely on one surface only, and while this surface might be damaged by fire, it would not extend sufficiently into the mass as to seriously affect the strength. It would seem, therefore, that, while Professor Woolson's experiments show us what occurs in the case of small cubes of green concrete submitted to an intense heat, such information to be of practical value should be carried on with large masses of concrete which have hardened for six or more months. I believe in that event we would find nothing like the destructive action found by Professor Woolson. These fire tests are usually much more severe than likely to occur, because it is doubtful whether such conditions would ever be obtained in an actual conflagration. If the fire were sufficient to develop a red heat in the concrete, it is more than likely that the surrounding temperature would be such that it would be impossible to get near enough to turn on a stream of water, as the water would be volatilized before it could reach the surface of the concrete.

Whether a building should be torn down after a severe fire, as suggested by Mr. Kent, is dependent on the damage which has been done, which can be determined by suitable inspection just as in the case of any other building. There are many examples of buildings of concrete which have successfully passed through severe fires.

A notable instance is the plant of the Pacific Borax Company at Bayonne, New Jersey. This plant consisted of a four-story building of reinforced concrete with wooden roof, door and window frames, as well as wooden posts for supporting two tanks of large capacity on the roof. Adjacent was a single-story building with reinforced concrete walls, covered partly by a wooden and partly by a corrugated iron roof, the latter being supported by a skeleton of steel. On each floor there was inflammable material which was practically consumed, as was all the wood work, including the twelve-inch wooden posts supporting the tanks on the roof. The steel skeleton completely collapsed, the columns folding up like a

Mr. Humphrey. ribbon. After the fire the building was cleaned, and the concrete appeared to be in good condition, showing no evidences of damage.

The character and age of the concrete has much to do with its fire-resisting qualities; the more dense and the older the mass the less water will be absorbed and entrained. Therefore a thoroughly hardened dense mass of mortar or concrete is likely to suffer little if any damage from the effects of fire.

It is to be hoped that Professor Woolson will continue his investigations on larger masses of older concrete.

Mr. Sabin. **MR. L. C. SABIN.**—One of the most important points brought out in this very instructive paper is the fact that it required nearly six hours for a temperature of $1,000^{\circ}$ F. to penetrate three inches of concrete. It is probable that the concrete used in these tests was of a better grade than is usually employed, and thus while stronger, it was also less porous, and, therefore, its conductivity was greater than the concrete ordinarily used in building construction.

The fact that the modulus of elasticity decreases more rapidly as the result of the application of heat than does the compressive strength is also an interesting one, for it means that a larger share of the load on a beam is transferred to the reinforcement relieving the concrete when the latter becomes weakened.

During this meeting I have been told, by someone whose name I do not now recall, of some experiments in which briquettes were heated and some broken while others were replaced in water and regained a portion of their lost strength. I am sure it would be interesting if my informant would say something about these experiments.

Mr. Lazell. **MR. E. W. LAZELL.**—In our laboratory briquettes of standard size made from three different brands of cement were exposed to a temperature of between $1,000^{\circ}$ and $1,200^{\circ}$ F., in such a manner that the flame did not come in actual contact with the briquettes. The briquettes were held at this temperature for a period of six to eight hours and then allowed to cool down slowly.

A part of each lot of briquettes were broken when they were cold, and these gave practically no strength. The remaining briquettes of each lot were then immersed in water and were broken after having been in water 7 and 28 days respectively.

The tensile strength results obtained from the 28-day tests were practically the same as those obtained from similar briquettes which had not been subjected to heat. This pointed to the conclusion that cement which has been de-hydrated at the temperature of the experiment with a loss of strength, regains its strength on being immersed in water 28 days, thus indicating re-hydration of the cement.

Mr. Lazell.

MR. SANFORD E. THOMPSON.—The size of the specimen largely affects the result. We all know that the surface of the concrete is disintegrated by fire to depths, varying with the conditions, from $\frac{1}{2}$ to $1\frac{1}{2}$ in. If the surfaces of a 4-in. cube are disintegrated to the depth of $\frac{1}{2}$ in. and this surface concrete rendered practically of no strength, the area of compression is reduced from 16 sq. in. to 9 sq. in., that is, nearly one-half, and the strength may be expected to decrease in the same ratio. If we assume the concrete to be affected to the depth of 1 in., its area of horizontal section is reduced from 16 sq. in. to 4 sq. in., or to one-fourth the original area. At a temperature of $1,500^{\circ}$ F., a disintegration of at least $\frac{1}{2}$ in. would be expected, and this of itself would explain the 50 per cent. reduction in strength shown in the diagram.

Mr. Thompson.

One of the most important subjects in fire resistance of concrete, and one which has never been satisfactorily investigated, is the comparative value of different rocks for the coarse aggregate. The question has often been raised whether a limestone mixture would not be changed to lime and the strength of the concrete utterly destroyed. While in these experiments the limestone mixture did not carry as high a load as the trap-rock concrete, it certainly did stand, when the reduction of area is considered, a very high stress throughout the test.

MR. G. P. HEMSTREET.—I should like to ask a question about the limestone and also make a little suggestion. Hudson River limestone is found on both sides of the river. That from the west side, which is now marketed in the greatest quantity in New York City, contains comparatively little carbonate of lime, and it is a very hard blue stone. That on the east bank contains a very large percentage of carbonate of lime and is a soft white stone. I should like to ask if it is known which limestone was used.

Mr. Hemstreet.

MR. WOOLSON.—Tompkins stone.

Mr. Woolson.

MR. HEMSTREET.—That contains very little carbonate of

Mr. Hemstreet.

Mr. Hemstreet lime, and is a very hard blue stone. Another thing I should like to suggest would be the effect of moderate heat applied for a long length of lime. I happen to know of several concrete chimneys lined with fire brick for a portion of their height. If they should be subjected to a temperature of 600 to 800° F. for several hours a day and for several years, is that concrete going to gradually become weakened by the effect of the moderate heat for a long length of time? I think if we could have some concrete cubes put in a chimney and kept there for a year, it might be an interesting experiment.

Mr. Cummings. MR. ROBERT A. CUMMINGS.—In connection with the fire resistance of concrete I should like to record a little experiment I made last year in Pittsburg. A gentleman interested in the utilization of the waste products of blast furnaces brought me two sample bricks, one composed of Portland cement and sand from slag granulate, and the other of Portland cement and ordinary river sand, both mixed in the proportion of one to three. He wanted my opinion of their relative values for a building.

There was but slight difference in appearance and strength. But I placed them in the hot coal furnace of the boilers in the basement of our office building. In fifteen minutes the brick composed of river sand and cement had become disintegrated and partly fused. I was unable to take it out of the furnace except in the shape of a clinker. At the same time the slag sand brick had not yet gotten beyond an ordinary red heat and it took about half-an-hour to reach a white heat. While at a white heat I took it out of the furnace and placed it in a pail of ice water. The effect was surprising as only the edges of the brick crumbled.

I think it is an interesting experiment and indicates that the waste product of the blast furnace in the shape of slag is a good material for fireproofing. I do not know the exact age of the bricks, but it was probably six months.

Mr. Lesley MR. LESLEY.—There are well-known results that have occurred in large fires which are practical tests of fire-proofing material. There have also been scientific tests conducted under the most skilful methods in a large way to determine this same fact. We all remember that the whole world was thrown into a turmoil some years ago by some laboratory experiments as to the effect of salt water upon Portland cement. It was feared that all

the docks and piers and everything built of Portland cement would fall away and would be disintegrated. In point of fact, the experiments disintegrated, but the docks and piers stood. Mr. Lesley.

The best illustration of this latter state of facts is shown in a series of papers read before the Engineering Congress, at St. Louis, by two Japanese engineers, who built some enormous harbor work, which took five or six years to finish. The docks are still standing. The writer drew an absolute distinction between the laboratory results of salt water experiments, and the actual results of work done in thousands and thousands of cubic yards of this material.

Now you have another illustration which goes to the effect of two different natural forces on concrete. One is the effect of frost, and the other is the effect of heat on small bodies of concrete. We all know that if you take a small, or even a large, body of concrete, the first thing that happens is that what we call a chemical action is set up, and these little needles—angular pieces—get together and do what we call setting. The moment that is under way along comes a powerful influence known as Jack Frost, who stops that operation and sets up another one, which takes the water which is necessary for this chemical action to go on, and turns it into little crystals, hardening the entire mass, thus suspending chemical development, which again begins when the mass thaws. Now, it may be that the surface of that concrete has been injured, but that does not in any way destroy it as a whole.

So, also, if you put concrete to the test of fire and drive out the water the surface may be injured, but the surface that is injured is so small in proportion to the amount of concrete actually used that it can always be discovered, and in fact no harm results. In a small cube there is a great deal of surface destruction proportionate to the mass, but in a large mass the destruction of the surface, either by frost or heat, is so light that it will not destroy the reliability of the mass.

Those are two points that seem to come to my mind on this question.

Therefore, if we take a mass of cement which is in the act of setting, for we are all aware that cement or concrete does not get its final set before very long periods, and that the water in the mass is producing the chemical action, it would be readily agreed that

Mr. Lesley. all the chemical action has not yet been completed at the expiration of so short a period as 30 days. Consequently, if small cubes of cement, in which the chemical action is not yet finished, are exposed in a fiery furnace at the end of so short a period as 30 days, it is a grave question whether, first of all, enough water is not driven off in the first few moments to deprive the mass, which is endeavoring to go on and complete its chemical action of setting, of the means so to do; or, in other words, if by driving off the water at so short a period and in such small bodies, the mass of concrete has not been deprived of its means of livelihood.

Those familiar with the testing of long time sets of briquettes can thoroughly appreciate how long it is before the actual final setting of the cement is completed. Sometimes a little white dry spot is found in the center of the briquette at the end of a year or eighteen months, and it may be three or four years before this little white mass extends over the whole surface of the briquette, showing that no more water is admitted into the interior, and that setting has finally been completed.

Mr. Patton. MR. ALFRED G. PATTON.—As a member of the National Fire Protection Association I am very much interested in this discussion.

We know that the resistance of steel is reduced very quickly as its temperature rises. In our laboratory at Chicago numerous tests were made as to the penetration of heat into the cement mass, and the effect of the heat on the reinforcement. We know that the floor load is carried by the reinforcement. The tensile strength or cohesive properties of the cement not being sufficient to carry any considerable floor load. The moment the temperature of the steel is raised to any extent, it reduces the resistance of the steel below the factor of safety and something is going to happen. We find that steel raised to a temperature of $1,400^{\circ}$ F. only retains about 10 per cent. of its resistance. The question is, how are we going to protect that steel from the action of the flames; not how far is the concrete going to resist their action. There have been buildings constructed of cement that failed under the fire test. In Baltimore there was a bank building that failed very decidedly. There were other structures, however, that stood the test of the fire. In one case the whole building was gutted, and the floor arches, beams and columns stood with practically no deterioration. Now there was some reason for that, and in our Committee

work some have come to the conclusion that, perhaps, the reason was from some inherent quality of the cement in one case, which permitted the heat to attack the steel work, and in the other case protected the reinforcement to such an extent that the arches failed to yield. It seems to us that there is greater necessity for protecting the reinforcement than worrying about the concrete. Mr. Patton.

I am glad to learn from Professor Woolson's experiment that cement is such a good non-conductor. We made a series of tests in Chicago, taking some beams, I think about 8" x 11 $\frac{3}{4}$ " section through which three steel rods were put, one 1 in. from the bottom, another 2 in. from the bottom, the third, 3 in. from the bottom. Through holes bored into the tops of the beams thermometers were inserted, which rested on the steel rods to note the rise in temperature of the rods. A temperature of about 2,000° F. was maintained under the beams for four hours. We found that the temperature of the steel where there was only 1 in. of concrete covering rose to the danger point, in a very short period. Where there were 2 in. of covering much better results were apparent. I am requested by Mr. Hexamer, President of the National Fire Protection Association, and by the Chairman of our Committee, to express to you our sincere sympathy in your investigations, and our earnest desire to co-operate in any way to ascertain the true possibility of cement as a factor in fire-proof construction.

MR. LEONARD C. WASON.—I just want to bring out one thought, especially in answer to the query of Professor Kent. In the designing of most columns which I have had to make, after determining the cross-section necessary for the strength, I have added about 1 in. on a side. By observation of the various fire tests which I have had an opportunity to see, I found the damage caused by the heat did not extend more than an inch into the surface. Therefore even if a column should lose 1 in. of surface by a severe fire, it still has in its center sufficient strength to carry the load, and that surface can be repaired by plaster without detriment to the entire construction. The attack of the heat is usually less severe on the columns than on the horizontal surfaces on the under side of floors. Therefore, the columns are not as likely to be damaged as the floor they support. Mr. Wason.

MR. RUDOLPH P. MILLER.—The New York Building Code prescribes a test for floors, which is designed to bring out the fire- Mr. Miller.

Mr. Miller. proof qualities of the materials entering into the construction. In framing the law, the protection of the steel frame structure now in general use was the main object aimed at. Reinforced concrete was practically unknown at the time the present law went into force. However, in testing reinforced concrete constructions, the requirements are followed as closely as possible. The prescribed test is essentially as follows:

A test structure of masonry, about fourteen feet wide by twelve to twenty feet long, of which the construction to be tested forms the roof, is erected. The necessary chimneys, draught openings, firing door and grate are provided. In this structure a fire of an average temperature of $1,700^{\circ}$ Fahrenheit, determined by pyrometer, is maintained for four hours. At the end of that time, water at a pressure of sixty pounds is applied to the underside of the construction for five minutes, through a one and one-eighth-inch nozzle; then the top is flooded, and the sixty-pound stream is again applied to the underside for five minutes. During this test the construction carries a load of one hundred and fifty pounds per square foot, for which it is designed. After the application of fire and water, the load is increased to six hundred pounds per square foot. The conditions of approval are that no fire or water shall have passed through the construction, the load shall have been safely sustained, and the permanent deflection after the removal of the final load shall not exceed two and one-half inches. This test on full-size constructions no doubt has many advantages over the laboratory test described in the paper, though compared with them it is perhaps a crude test.

Since September, 1896, more than fifty such tests have been made under the supervision of the New York Building authorities, the majority of which were on cinder concrete construction. The practically uniform results in these cases have established beyond doubt the thoroughly fireproof character of the cinder concrete construction.

The results on the stone concrete have not been so satisfactory. Out of fourteen tests eight were successful. The failures were due probably in most cases to the fact that the test was made too soon, before the concrete had set sufficiently. In all the tests on stone concrete, water was driven off in great quantities during

the first half-hour. When the concrete has not had a chance to dry out sufficiently the expulsion of the water and conversion into steam are likely to disrupt it. Even in the successful tests the concrete was flaked off on the surface exposed to the fire, for a depth of about one inch. It, therefore, becomes of great importance that a sufficient thickness of concrete shall be provided around the metal reinforcement. Mr. Miller.

Another matter that deserves some attention is the time that should be allowed for the setting of the concrete before the test is made. A maximum limit should be fixed dependent on the interval between construction of a building and its occupancy in ordinary cases. New York practice in this respect was formerly thirty days, but more recently a longer time has been given before testing.

MR. WOOLSON.—There are just one or two points brought out by Mr. Miller that I wish to speak about. With regard to water in the concrete: where the test was made in thirty days, we have repeatedly noted in large floor tests, that the water has come out to such an extent that on a floor of 15-ft. span we have had anywhere from $\frac{1}{2}$ to $\frac{3}{4}$ in. of water on top during the first two hours of the test. That water came up out of the concrete. Whether it was held there mechanically or was water of crystallization dissociated by the heat, I do not know, but it is quite evident that the concrete was too green. This accumulation of water was particularly marked where the concrete stood during the early spring months and was thoroughly wet. The older the concrete, the better results we get. The only question is, what the age limit should be at which we should test it. Mr. Woolson.

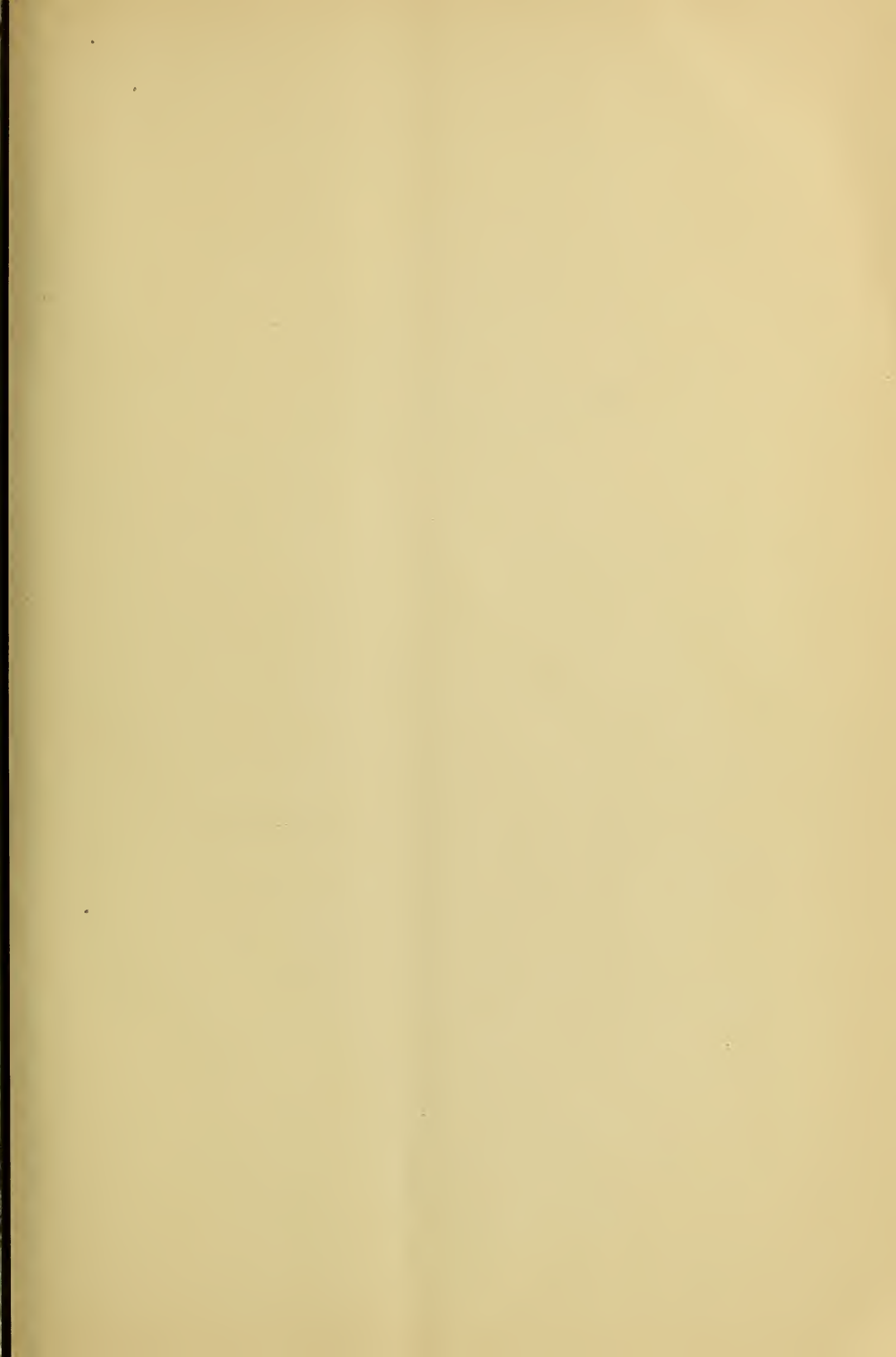
Now, a word with regard to Mr. Kent's query. I might say that we have made repeated tests upon full-size floor units that Mr. Miller has spoken of, where we applied the heat for four hours, varying from 1,700 to 2,000° F. After the buildings cooled we loaded them again to 600 lbs. per sq. ft., and they carried the load successfully. That would seem to show that there was more than 50 per cent. of strength left in the concrete. In my judgment, the resistance to heat comes from the non-conductivity of concrete. The upper part of the floors were injured to a very slight extent. We found that water on red-hot concrete would break off some of the surface. In some cases,

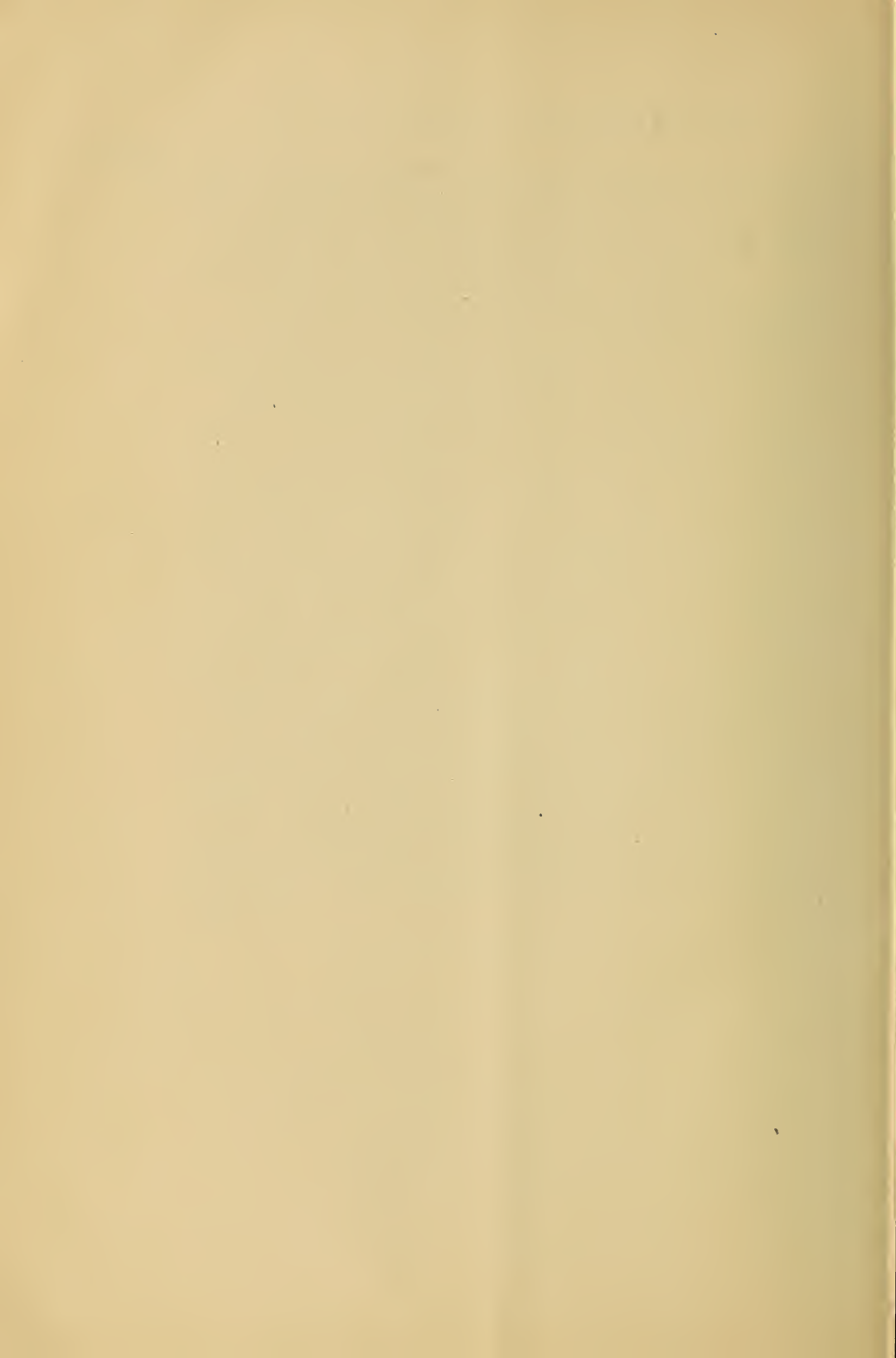
Mr. Woolson. where girders were used, it knocked the concrete from the bottom part of the girder, and exposed the metal. A subsequent examination of buildings after the ten minutes application of water which we employ in our tests, showed the concrete was much better where the water had been applied than where it had not.

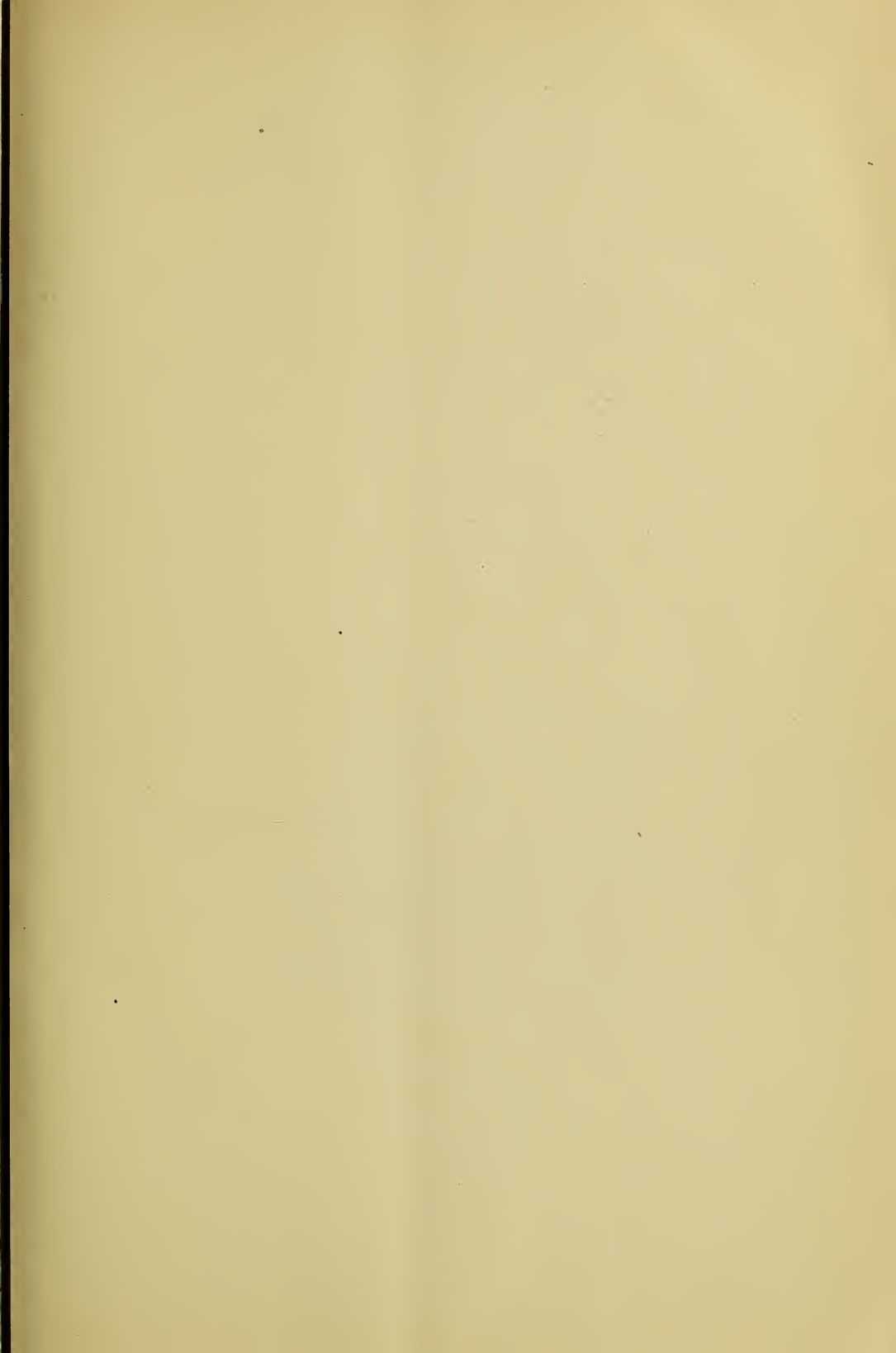
In the tests for conductivity it took about four hours to penetrate to the middle of a 6-in. block; in other words, to go through 3 in. of concrete where there was no possible chance for radiation, and the heat was coming in on all sides.

With regard to the sand and cement mixture that has been spoken of. In our testing station we have a building 14 ft. long, by 9 ft. wide and 9 ft. high, which is used for testing partitions. The ceiling and end walls are permanent; the side walls are removable, and new partitions are put in. The ceiling and end walls are made of a 1:4 mixture of sand and cement, 4 in. thick. We have had eight or nine tests in that building, averaging 1,700°F. for half of the time, and gradually approaching that during the rest of the time. Those walls are still in excellent condition; good for an indefinite number of tests, as far as I can see. I shall have to move the building soon and must tear it down; I am regretting the job I have on my hands, it is in such good condition.

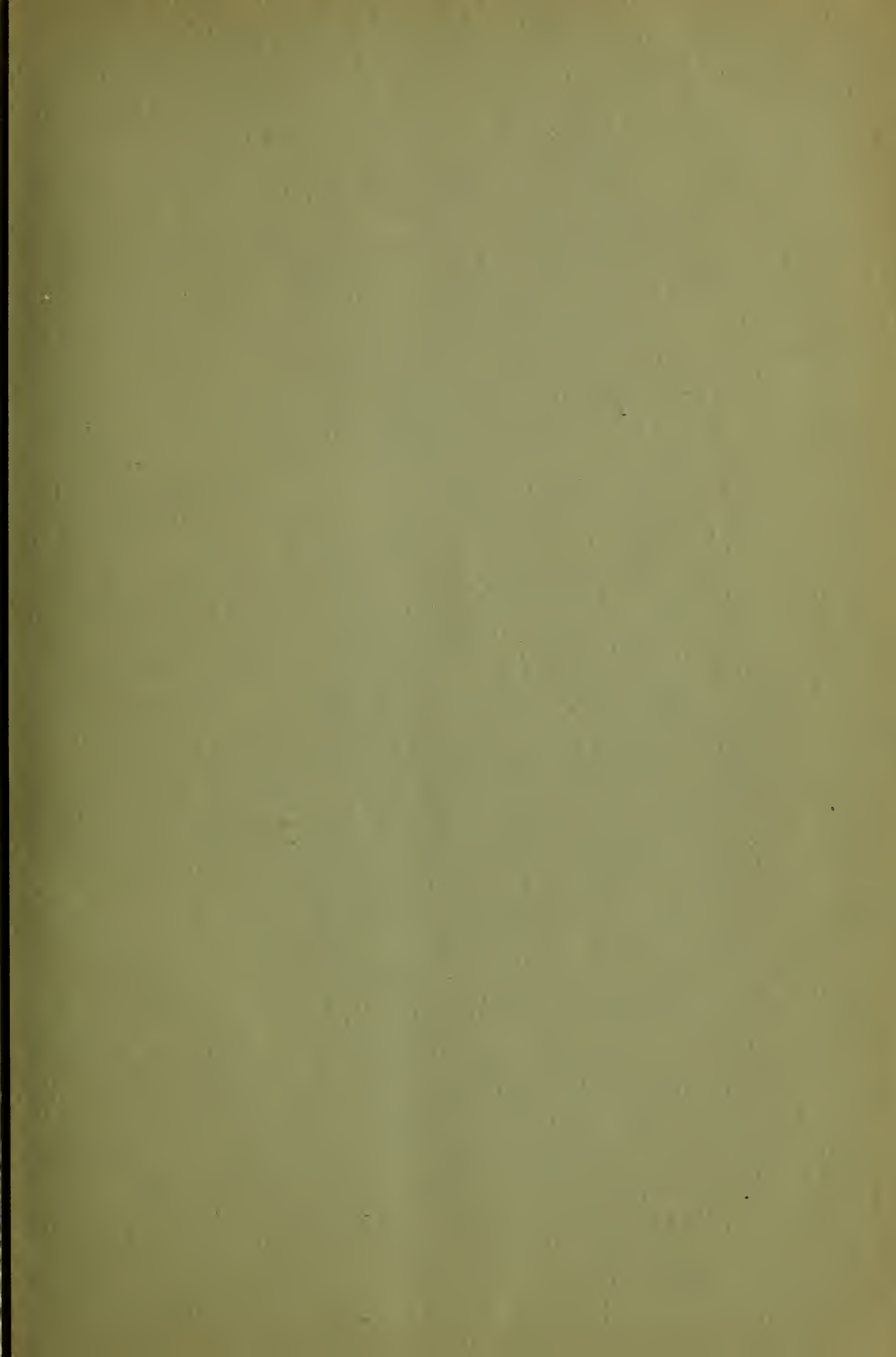
The question has been raised regarding laboratory tests not being comparable with large practical tests. I agree thoroughly on that point. The only idea of these tests was to ascertain, if possible, what the effect on the specimen of concrete would be as to its elasticity and its strength, provided we could give it a uniform heat all through. That is all these tests bring out. They do not affect, I think, the general problem of concrete as a mass construction.











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